High-Frequency Propagation in the Ocean Waveguide

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LONG-TERM GOALS

The long-term goals are to advance our understanding of the nature of high-frequency (8-50 kHz) sound propagation in the ocean waveguide, with emphasis on surface, bottom, and volume effects on the forward-propagated field.

OBJECTIVES

The objective of this work is to learn as much as possible about the channel impulse response (or transfer function) and its dynamics. Ideally, we would like to characterize the behavior as a function of 1) source/receiver geometry, 2) arrival angle, 3) carrier (central) frequency, 4) ocean volume structure, 5) bottom type, and 6) boundary dynamics, including effects of surface waves and bubbles. The band of interest has a variety of applications, including mine countermeasures, tracking odontocetes in navy ranges, and bottom mapping. However, the core application of interest in this program is for acoustic communications.

APPROACH

This year's work has focused on the following areas: 1) initial matched-filter processing of Makai data to produce the time-varying channel impulse response, 2) development of two numerical solutions for time-dependent pulse reflection and scattering off a rough surface using a) an exact Helmholtz-Kirchhoff integral equation and b) a Kirchhoff approximation (work with M. Siderius), 3) development of high frequency (HF) ambient noise models for use in geoacoustic mapping algorithms (w/ M. Siderius), 4) application of the virtual source method to produce exact benchmark solutions for range-dependent elastic waveguides (w/ Ahmad Abawi), and 5) development of an HF Vector Gaussian Beam model for use in modeling vector sensor array performance (w/ Paul Hursky). In addition, the author participated in the Monterey Bay 06 Experiment collecting data to support the HF modeling work for acoustic communications.

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The research done under this contract covers a wide variety of areas, all linked by the common thread of HF acoustics. Considering space limitations, we will include results from a subset of the activities, beginning with the rough surface modeling.

The community talks loosely about scattering from rough surfaces although there are really two very different mechanisms involved that relate to temporal coherence and spatial coherence. To be clear on these mechanisms, it is useful to think about the extremes of 1) a moving but flat surface, and 2) a static but rough surface. One does not normally think of a flat surface as a scatterer; however, the sound reflected in the moving mirror of the surface is *Dopplerized*. That distortion causes an apparent energy loss when the signal is viewed through a matched filter. In contrast, the perfectly static surface induces no time-dependent distortion of the signal. As a result, a tonal waveform is always heard as a pure tone. However, the surface roughness breaks up the wavefront causing a loss of spatial coherence. It is tempting to claim that these effects are uniquely interesting for the high frequencies used in acoustic modems that are currently in vogue. However, these effects are actually very important for many acoustic systems from low to high frequencies. Acoustic comms waveforms simply highlight the shortcoming of existing scatter models, many of which predict absurd losses when scaled to the HF band. Then the intrinsic scientific flaws are clearly revealed.

WORK COMPLETED

In this work, we are modeling both the temporal and spatial coherence problems, not just independently, but rather simultaneously. A key set of these tools is being built around the BELLHOP Gaussian beam model. However, it should be emphasized that these tools provide a hierarchy of solutions with increasing sophistication. The base model is nothing more than a direct ray/beam solution for interaction with a rough, dynamic surface. The more sophisticated approaches in the family, use Gaussian beams to provide a point-to-point Green's function with refractive effects. However, because the Green's function is just a connector, that approach can handle scattering effects in a nearly exact way. To talk about the various approaches, we consider: 1) specular, 2) Kirchhoff approximation, and 3) exact Helmholtz-Kirchhoff integral equation. Specular implies that a ray hits a facet of the surface and reflects off it, as if it were a piece of a broken mirror. At the other extreme, we have the exact Helmholtz-Kirchhoff integral equation that considers a ray fan from the source and receiver that connect each to the surface. The Helmholtz-Kirchhoff integral equation requires that all those connections occur so that the full wave equation is satisfied. The Kirchhoff approximation is sort of a Goldilocks solution that considers a fan from the source but assumes the illuminated (ensonified) surface reacts in a simple way, with each point acting like a point-source radiator. The field at a given receive position draws not just upon the specular, but also a continuum of non-specular arrivals from every radiator on the surface. Finally, to complicate this further, this family of tools can substitute BELLHOP ray/beam solutions that allow for refractive effects, and further, sample these solutions for time-evolving surfaces to produce Dopplerized waveforms.

It is difficult to express this family of options in a simple way. The important take-away is that there is a family of solutions with very different approximations and computational burden that all target the problem of providing a time-series simulator for rough surfaces.

RESULTS

It is important to keep in mind in the following discussion that our prime motivator is to handle a ***dynamic***, rough surface over a waveguide with its own refractive effects. The techniques we are

discussing have a history in a frozen, isospeed ocean. However, our work generalizes these techniques by allowing for surface motion and by using a Green's function that includes refractive effects.

Figure 1 shows several of the different scattering options that have been implemented for rough surfaces. The shape of the rough surface is shown by the red line. Note that the figures on the left column all use the same surface with a fairly gentle variation, while the figures in the right column have a much more rapidly varying surface. From top to bottom we have a hierarchy of solutions with the most accurate (and most time consuming) at the top. In particular, the top row is the exact Helmholtz-Kirchhoff integral equation solution (following precisely a nice development by E. Thorsos). This solution is the benchmark; however, the integral equation links every point on the surface to each other and is an unlikely candidate for use in a time-series simulator. The middle panel makes the classic Kirchhoff approximation in which each point on the surface radiates according to a simple formula related to its ensonfication. One can see that this approximation does well for both the gentle and rapidly-varying surfaces. This Kirchhoff approximation generalizes nicely to the moving surface over a refractive medium. The lower panel uses a Gaussian beam tracing approximation. This is by far the simplest and fastest approach and also easily generalizes to the moving surface problem. However, we can see that in this basic implementation it does a poor job for the rapidly-varying surface (work joint with M. Siderius).

A second method we have used for complicated boundaries is the "virtual source method." This is very closely related to the Helmholtz-Kirchhoff integral equation, but takes a different view, leading to different insights. An example of the capabilities of this method is provided by an elastic wedge problem shown in Figure 2. Despite years of work, there is still only limited capability for modeling such elastic waveguide problems for Navy applications. The virtual source method provides one of the few capabilities for providing benchmark solutions. The lower panel of Figure 2 shows the resulting compressional (P) and shear (S) wave potentials for this case, showing the coupling of acoustic energy in the water column to P and S waves in the elastic bottom. This calculation is done at low frequencies; however, we have also used this approach to study "glints" due to surface waves at high frequencies (work joint with Ahmad Abawi).

Another thrust of this work has been to develop Gaussian beam algorithms for vector sensor arrays. These arrays sense the displacement field in the ocean rather than just the scalar pressure field and are expected to be useful for both low and high frequency acoustics and for a variety of applications, including acoustic communications. To generalize the Gaussian beam method, we construct *vector Gaussian beams* which are essentially the gradient of a convention pressure beam. An example of such a beam is shown in the top panel of Figure 3 where we have plotted just the z-component. As in the conventional Gaussian beam method, we construct a fan of such beams, each with a different take-off angle. The total acoustic field is then computed by summing each of the beams. The resulting z-component of the displacement field is shown in the lower panel of Figure 3. Note the dipole pattern in the sensitivity of the z-component (work joint with Paul Hursky).

Results of this research have been reported in several journal articles (appeared or accepted this year) and about a dozen conference presentations, including a plenary talk at the European Conference on Underwater Acoustics. About six short papers were also prepared for the ECUA conference proceedings mostly documenting the Makai Experiment. Finally, work has continued on revisions to the text *Computational Ocean Acoustics* in preparation for the new edition.

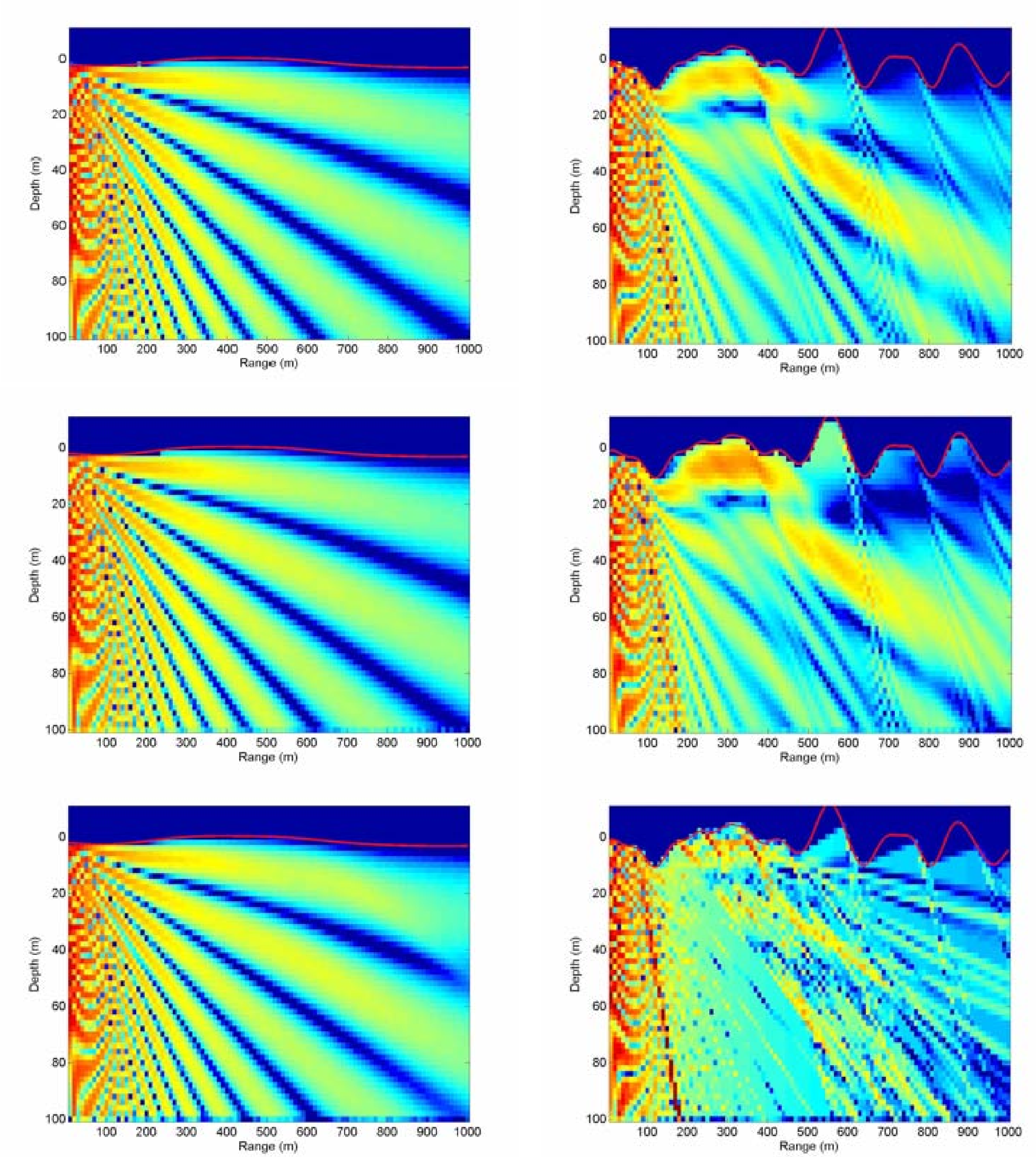

Figure 1. Comparison of exact Helmholtz-Kirchhoff integral equation solution (top row), Kirchhoff approximation (middle row), and BELLHOP (lower row). Surface roughness was increased for the right column.

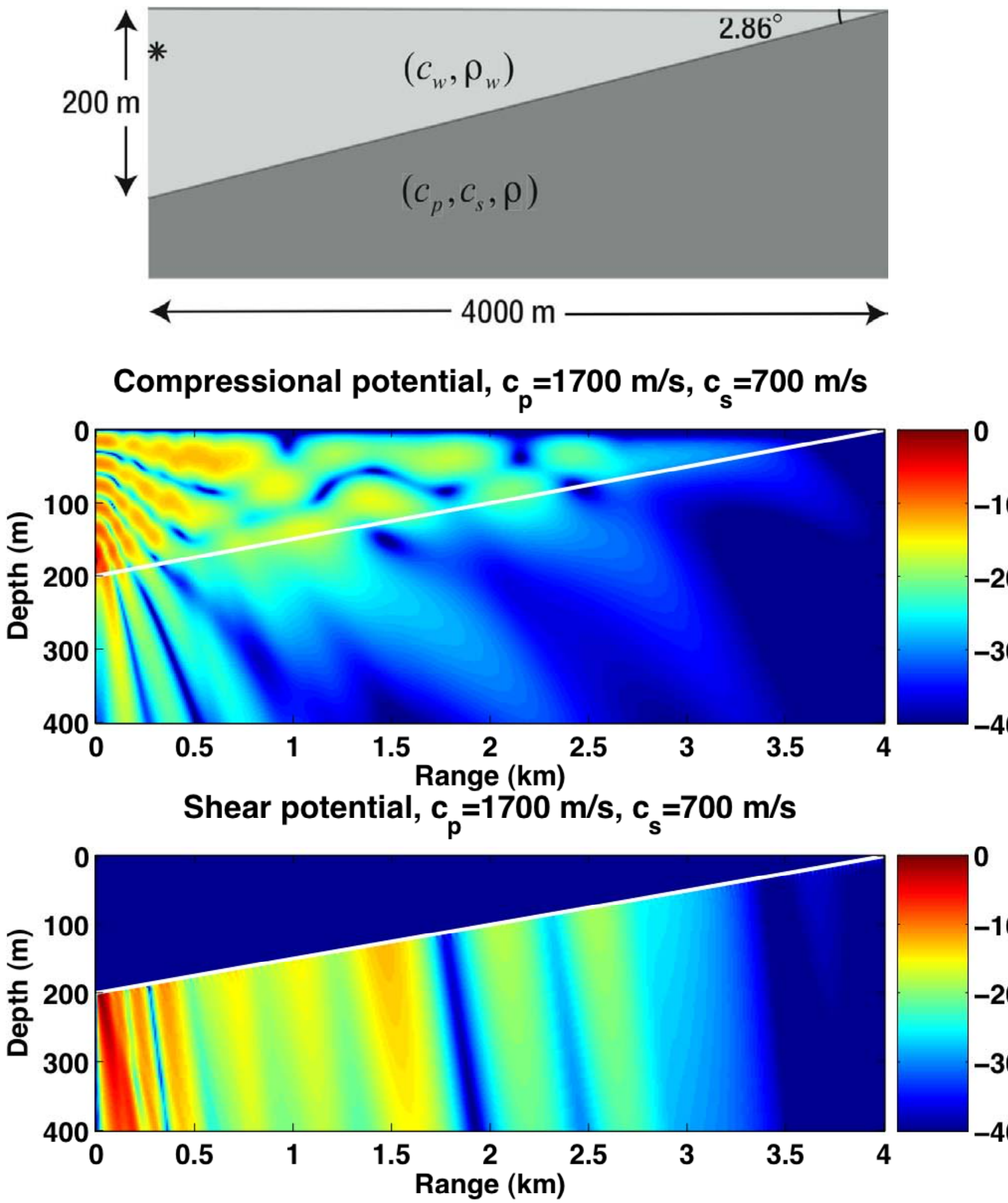

Figure 2. Virtual source method for propagation in irregular waveguides. Top panel: environment geometry. Lower panels: compressional and shear potentials showing coupling from acoustic energy in the water column to P and S waves in the elastic bottom.

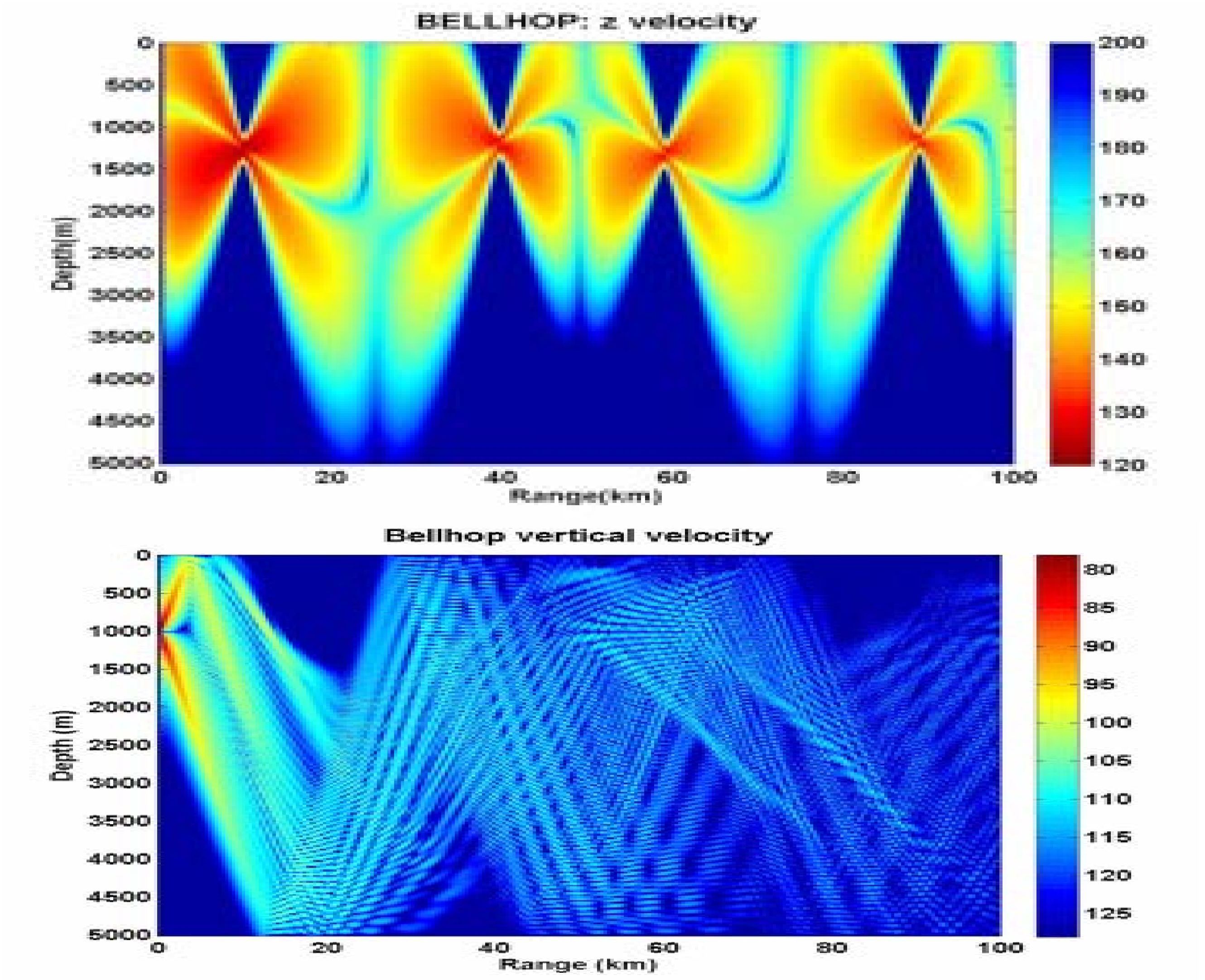

Figure 3. Vector Gaussian beam tracing: a fan of vector Gaussian beams is summed to yield the total vector field. The upper panel shows the z-component of an individual vector Gaussian beam. The lower panel shows the z-component of the total field. Note the dipole pattern in the receiver sensitivity.

IMPACT/APPLICATIONS

There are a variety of Navy systems that operate in the HF band. However, a key application of interest is acoustic modems. The MIMO testing is particularly valuable because of the large number of transmitters used in the source array and because of the variety of modulation schemes tested.

TRANSITIONS

This work is being conducted in parallel with the 6.2 SignalEx program (322OM) on underwater acoustic communication so that lessons learned about the basic propagation physics can be immediately linked to modem performance. The SignalEx program in turn transitions to operational modem development through other 6.3/6.4 navy programs.

RELATED PROJECTS

Work reported here is linked to other programs, such as PLUSNet for the MB06 experiment, ONR's Vector Sensor Program (P. Hursky), and an ONR program on geoacoustic inversion (M. Siderius). The virtual source method has largely been developed under an MCM program.

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